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Three-nucleon force effects in the FSI configuration of the $d(n, nn)p$ breakup reaction

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Abstract

We investigated three-nucleon (3N) force effects in the final state interaction (FSI) configuration of the $d(n, nn)p$ breakup reaction at the incoming nucleon energy E_n= 200 MeV. Although 3N force effects for the elastic nucleon-deuteron scattering cross section at comparable energies are located predominantly in the region of intermediate and backward angles, the corresponding 3N force effects for the integrated FSI configuration breakup cross section are found also at forward scattering angles.

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1 Introduction

Our studies of 3N continuum are based on the exact solutions of the 3N Faddeev equation in momentum space. They began in the 1980s and in the 1990s were performed with several realistic two-nucleon (2N) forces: the AV18 [1], CD Bonn [2], NijmI, NijmII, Nijm93 and Reid93 [3] potentials. The results of these studies (see for example Refs. [4, 5]) proved that predictions of 3N scattering observables are in good agreement with the data at input nucleon energies below about 30 MeV. The situation changed at highier energies, where theoretical predictions using only 2N forces clearly deviated from the data [6, 7]. In particular, strong discrepancies between such calculations based on 2N potentials and the data were found in the minimum of the elastic scattering cross section. For energies smaller than approximately 140 MeV the agreement between theoretical predictions and the data for this observable was regained, when the Tucson–Melbourne (TM) [8] or Urbana IX [9] 3N force (3NF) models were included in the 3N Hamiltonian [10]. Thus the studies in Ref. [10] provided strong evidence for the action of 3NF in 3N scattering. However, the description of many polarization observables and generally the description of the data at still higher energies was not always satisfactory [5, 11].

At high energies one could expect deficiencies in the nonrelativistic Faddeev approach. That is why we constructed a relativistic framework in the form of relativistic Faddeev equations [12–18] according to the Bakamjian-Thomas theory [19]. However, the relativistic effects turned out to be generally small and insufficient to significantly improve the data description.

Neither TM nor Urbana IX could be considered merely as phenomenological 3NF models, since they are based on a meson theoretical picture. However, it was pointed out that these 3N forces were not consistent with the widely used 2N forces. The QCD Lagrangian with massless quarks possesses chiral symmetry. This chiral symmetry is explicitly broken because of the quark mass terms. This feature of QCD and the mechanism of spontaneous chiral symmetry breaking inspired Weinberg to use effective field theory of QCD in the form of chiral perturbation theory as a tool to construct nuclear interactions. This idea was then implemented by many physicists, who strove for construction of precision 2N and many-nucleon potentials. We mention here work by van Kolck [20], the early model of the Bochum-Bonn group [22] and the nuclear forces developed by the Moscow (Idaho)-Salamanca group [21]. In particular Epelbaum and collaborators for the first time used chiral 2N and 3N forces to study nucleon-deuteron scattering [23].

Currently the investigations of few- and many-nucleon systems with the new generations of chiral potentials from the Bochum-Bonn group are carried out within the LENPIC project [24]. More information about this initiative, coordinated by E. Epelbaum and J. Vary, can be found in the contribution to this conference by J. Golak et al. [25].

In the present contribution we studied in detail one of the most important kinematical configurations of the nucleon-induced deuteron breakup reaction, namely the final state interaction (FSI) configuration. We considered the case, where two neutrons emerged with the same momenta, forming quasi dineutron, while the final proton momentum was restricted by four-momentum conservation. Our purpose was to estimate 3NF effects for this effectively two-body reaction.

2 Final State Interaction configuration

We investigated 3NF effects in the FSI configuration of the $d(n,nn)p$ breakup reaction. To this end we obtained solutions of the 3N Faddeev equations [4] with the CDBonn nucleon-nucleon potential [2] and the Tucson-Melbourne 3NF [8]. From these solutions one can construct not only the elastic scattering observables but also the observables for the breakup process. In this contribution we restrict ourselves to an integrated breakup cross section around the final state interaction condition for the two emerging neutrons:

$$\frac{d^2\sigma}{d\Omega_1 d\Omega_2} \equiv \int_{S_0-\Delta S}^{S_0+\Delta S} \frac{d^3\sigma}{d\Omega_1 d\Omega_2 dS} dS \bigg|_{\Omega_1=\Omega_2} \qquad (n+d \to (nn)+p). \tag{1}$$

Here Ω_1 and Ω_2 represent the directions of the momenta of the outgoing neutrons 1 and 2, respectively. Note that for fixed Ω_1 and Ω_2, the energies of the two neutrons, E_1 and E_2 lie on a certain curve, the so-called "kinematical locus". Choosing an appropriate starting point where by definition $S=0$, the S parameter is calculated as a distance taken along the curve from its starting point:

$$S = \int dS = \int \sqrt{(dE_1)^2 + (dE_2)^2}\,. \tag{2}$$

This arc-length variable S defines uniquely the three-nucleon kinematics, yielding a specific (E_1, E_2) point on the kinematically allowed curve in the (E_1, E_2) plane. The FSI occurs for the

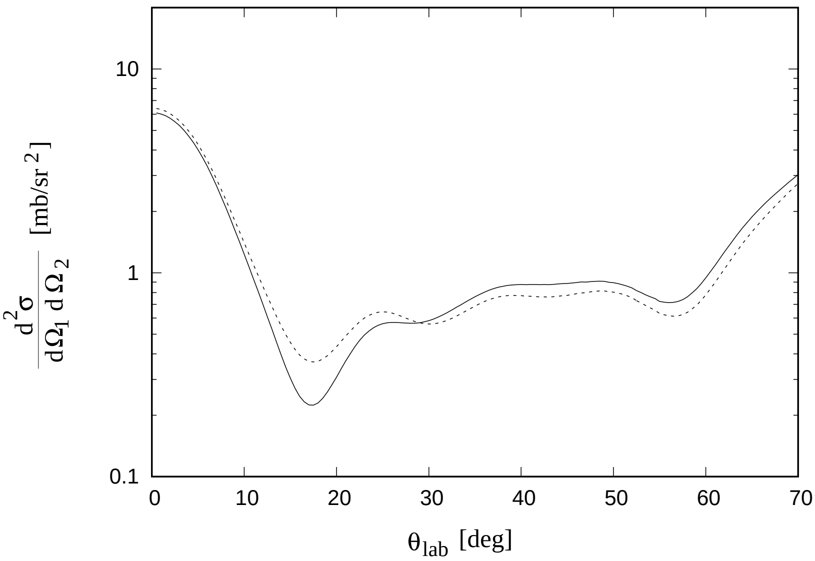

Figure 1: The integrated final state interaction configuration breakup cross section for the incident neutron laboratory kinetic energy E_n= 200 MeV. The theoretical predictions based solely on a 2N interaction (here the the CDBonn potential [2]) are represented by the dotted line, while the results obtained with the 2N potential augmented by the Tucson-Melbourne 3NF [8] are shown with the solid line.

condition $E_1 = E_2$, where $S \equiv S_0$.

Figure 1 shows the breakup cross section of Eq. (1) for the incident neutron laboratory energy E_n=200 MeV resulting from integrations over the S variable in the interval $S_0-\Delta S, S_0+\Delta S$ with the width parameter ΔS= 20 MeV. The angle θ_{lab} is the common laboratory scattering angle of nucleons 1 and 2, for which the FSI condition is realized.

We found a large deviation between the theoretical predictions for the FSI cross section including or not including 3NF. Although the 3NF effects for the elastic scattering cross section are located predominantly in the region starting from middle up to backward scattering angles, the 3NF effects for the integrated FSI configuration breakup cross section are found also at forward scattering angles.

3 Conclusion

We found a large deviation between the theoretical predictions including or not including 3NF. Although the 3NF effects for the elastic scattering cross section [6, 7, 26, 27] are most pronounced for the intermediate and backward scattering angles, the 3NF effects for the integrated FSI configuration breakup cross section are found also at forward scattering angles. We hope that our results can be in future confronted with experimental data.

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